FROM RESEARCH TO INDUSTRY

The NEνFAR project:
New Evaluation of ν Fluxes At Reactors

Investigation of the ILL spectra normalization

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Outline

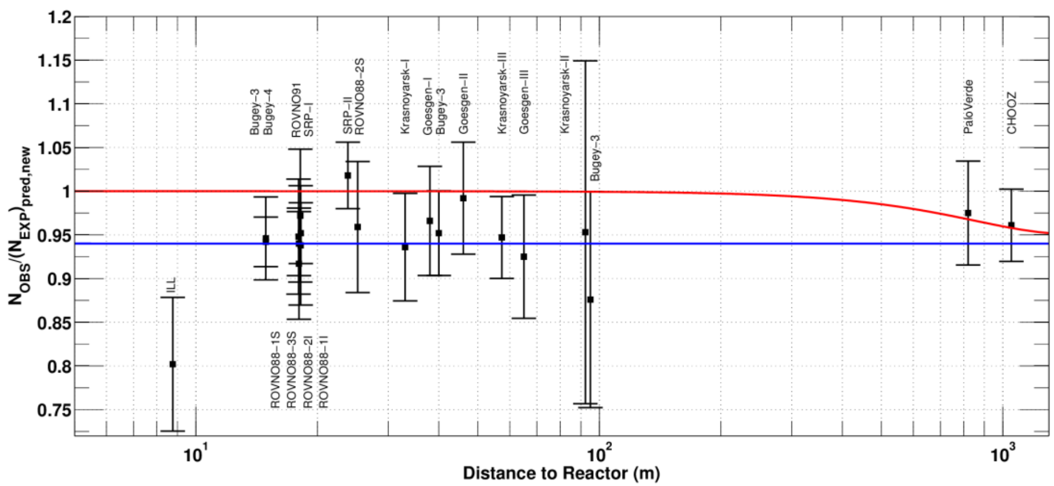
1. Normalization anomalies of reactor $\bar{\nu}_e$ experiments
2. The ILL spectra measurements
3. Investigation of the ILL spectra normalization with dedicated simulations of the RHF reactor
4. Conclusions and perspectives

Reference reactor $\bar{\nu}_e$ spectra: normalization anomalies (1)

2 major review of reactor $\bar{\nu}_e$ calculation in 2011 (based on ILL e⁻ spectra measurements):

- T. Mueller et al. (Phys.Rev. C84 (2011) 024617) / P. Huber (Phys.Rev. C84 (2011) 024617)

  + ab-initio ^{238}U calculation / off-equilibrium calculation for T. Mueller et al. paper



[G. Mention et al. Phys.Rev., D83 :073006, (2011)]

⇒ **Both agree on new global normalization: +3% shift**

⇒ **Also global agreement on new error calculation**

« new evaluation (Mueller et al.) »
⇘ **N_{obs}/N_{pred} = 0.943 ± 0.023 (1σ)**

« old evaluation (Schrekenback/Vogel) »:
⇘ **N_{obs}/N_{pred} = 0.976 ± 0.024 (1σ)**

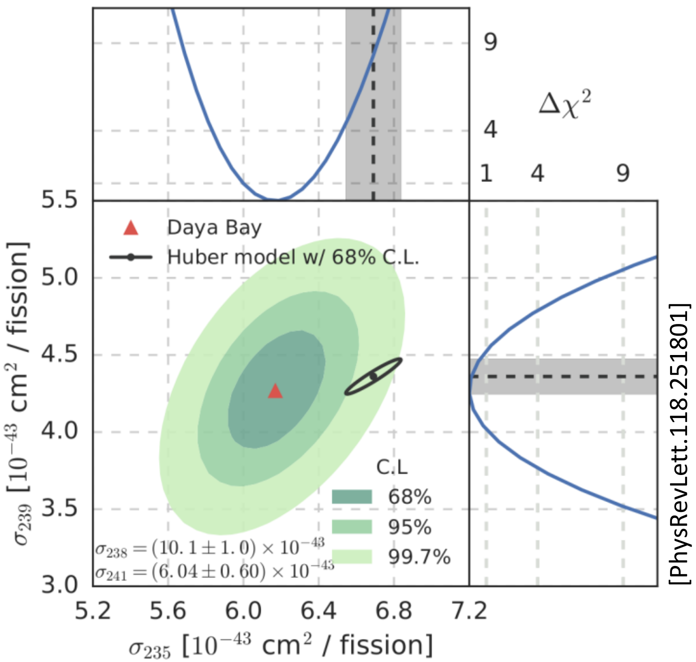
⇒ **Reactor anomaly: overall ∼6% difference between data and expectation**

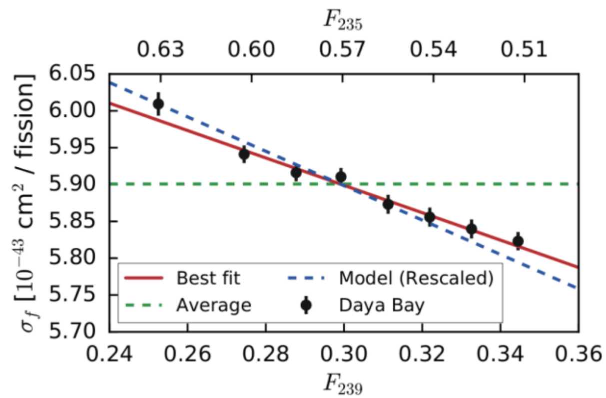
Main Hypothesis:

- Underestimation of $\bar{\nu}_e$ spectra uncertainties
- Existence of sterile neutrino with $\Delta m^2 \sim 1$ eV² et $\theta_{new} \sim 10°$

Reference reactor $\bar{\nu}_e$ spectra: normalization anomalies (2)

- **Fuel evolution measurement by the Daya Bay experiment**





- $\langle \sigma_f \rangle^{DB}_{235U} = (6.17 \pm 0.17).10^{-43}\ cm^{-2}.fission$
  $\Rightarrow$ 7.8% lower than H+M model

- $\langle \sigma_f \rangle^{DB}_{239Pu} = (4.27 \pm 0.26).10^{-43}\ cm^{-2}.fission$
  $\Rightarrow$ consistent with H+M model

$\Rightarrow$ « Relative » anomaly across individual isotope normalisation

$\Rightarrow$ Indication of a « preference for an incorrect prediction of the ^{235}U flux as the primary source of the reactor anomaly »

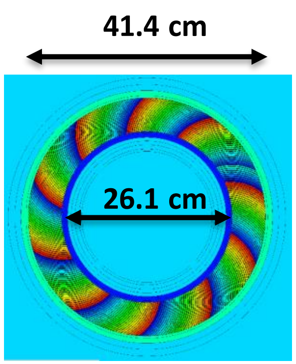
Also: several publication with slightly different conclusions or reviewed significance:
[A. Hayes & al., PhysRevLett.120.022503] , [C. Guinti & al., JHEP10(2017)143]

The ILL Reactor

The Institut Laue-Langevin (Grenoble, France):

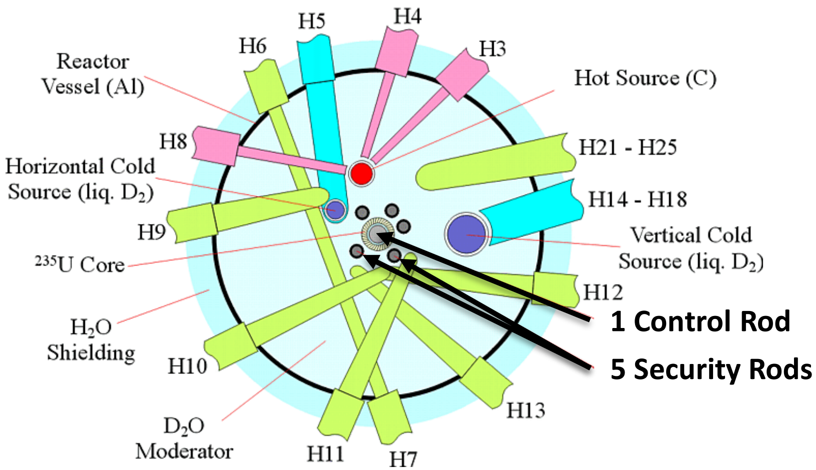
- 58.3 MWth research reactor
- **Huge thermal flux: 1.5×10^{15} neutron/cm²/s**
- Fuel cycle: 50 days
- **Heavily instrumented**

- **Fuel:**
  - Single annular fuel element: 280 curved plates
  - 'Bomb-grade' highly enriched uranium (HEU): UAlx with **^{235}U enrichment at 93%**
  - Fissile part height: 80 cm



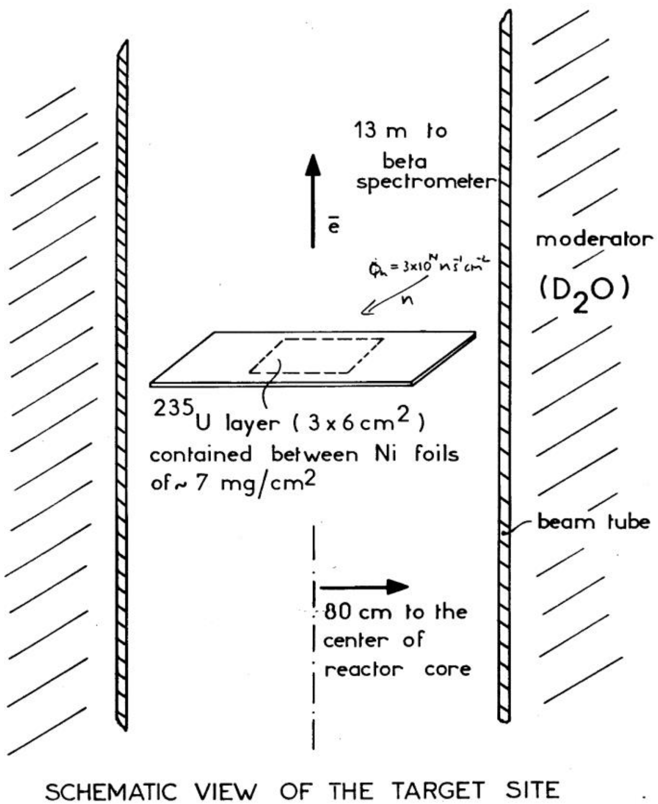
- **Moderator/coolant/reflector:**
  - Heavy water (D2O)

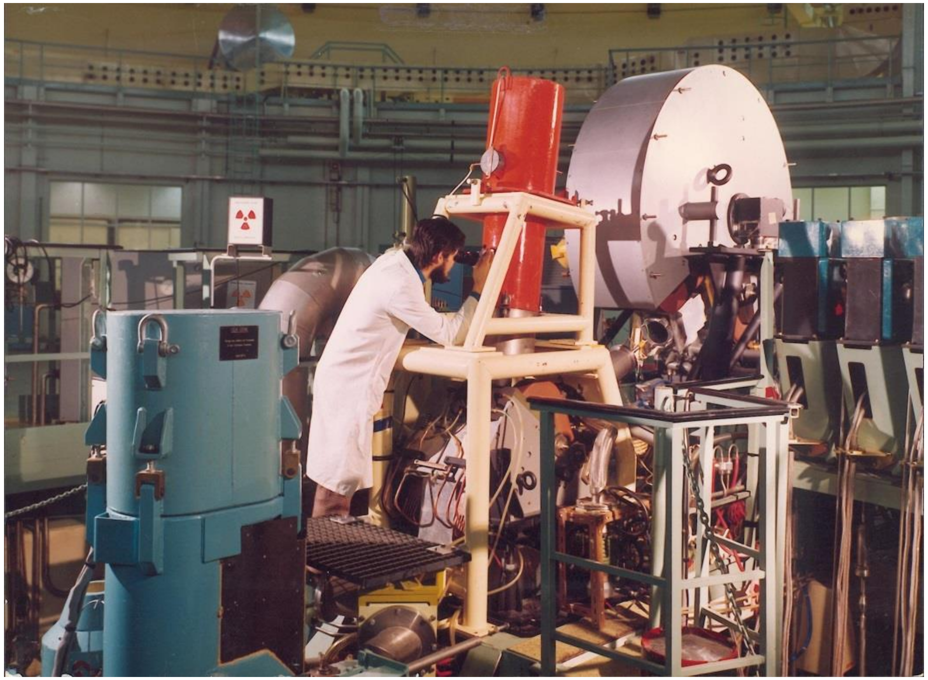
- **Reactivity control:**
  - Borated zone along each fuel element
  - Single control element



Top view of the RHF (High Reactor flux) and its instrumentation

The BILL EXPERIMENT





Magnetic BILL spectrometer at ILL, 1972-1991

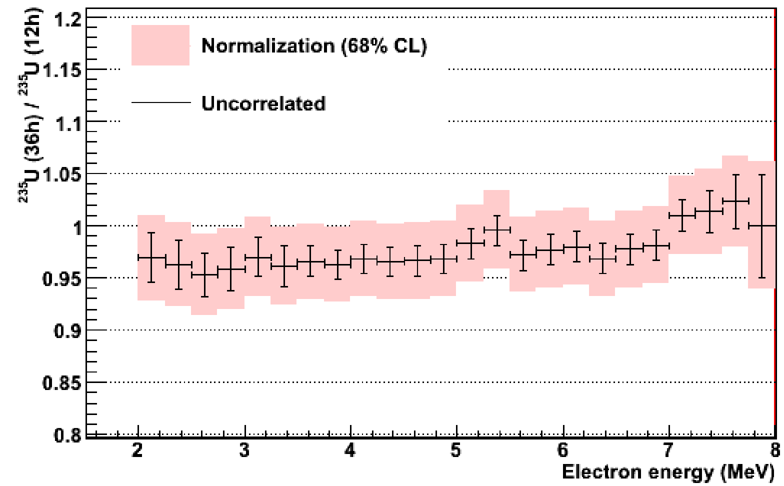
(Electron detector in focal plane: multi chamber proportional counter in transmission, rear mounted scintillator in coincidence)

- Layer irradiated in a beam tube under vacuum at 80 cm of the reactor Z-axis
- **Exact location of the beam tube in the reactor unknown**
- Fission products stopped in the Ni foils, e^- guided through the beam to BILL at 13 m

The ILL electron-energy spectra (1)

Four measurement performed at the ILL in the 80's

- **^{235}U(1):** [1] *K. Schreckenbach et al., PLB99 (1981) 251*
  - Normalized on: **^{197}Au(n,e$^-$)^{198}Au**
- **^{235}U(2):** [2] *K. Schreckenbach et al.", PLB160 (1985) 325*
  - Normalized on: **^{207}Pb(n,e$^-$)^{208}Pb and β-decay following ^{115}In(n, γ)^{116m}In**
- **^{239}Pu:** [3] *F. Feilitzch et al.", PLB118 (1982) 162*
  - Normalized on: **^{197}Au(n,e$^-$)^{198}Au and ^{115}In(n,γ)^{116}In**
- **^{241}Pu:** [4] *A.A Hahn et al., PLB218 (1989) 365*
  - Normalized on: **^{207}Pb(n,e$^-$)^{208}Pb and ^{115}In(n,e$^-$)^{116m}In**



Ratio of the two measured electron-energy spectra for ^{235}U from [1] (36 h) and [2] (12 h).

Spectra normalization (Number of beta particles per fission)

- Irradiation of calibration targets with well-known partial cross sections to thermal neutron capture
  ⇒ bypass the reactor neutron flux knowledge

$$N_\beta = \frac{N_f}{N_{st}} \frac{n_{st}}{n_f} \boxed{\frac{\alpha\sigma_{st}}{\sigma_f}}$$

st, f: *calibration and fissionning target*

- σ_f, σ_{st}: mean cross-section for a thermal neutron flux
- n_f, n_{st}: number of atoms of the target
- N_f, N_{st}: measured counting rates
- α: internal conversion coefficient (ICC) or beta branching ratio to the relevant state for the beta decay

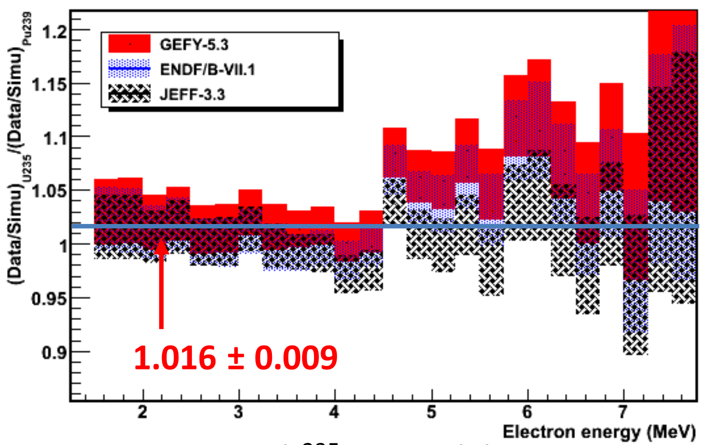
The ILL electron-energy spectra (2)

Comparison of the two ^{235}U measurements normalization

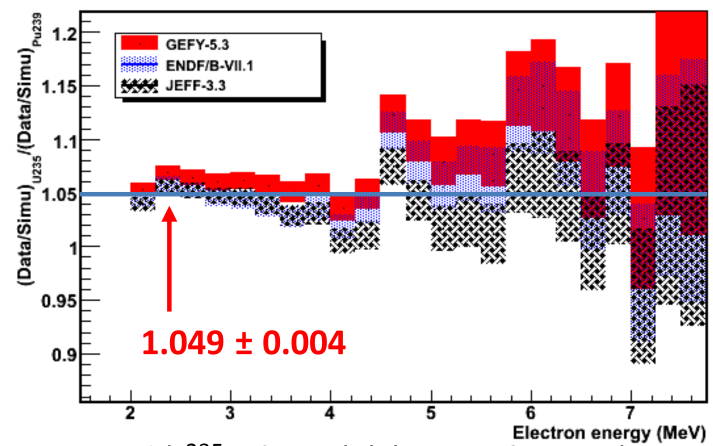
Energy-spectra modelisation (simulation):

$$S_{tot}(E_e) = \sum_{FP} Y \times \sum_{branch} BR \; S(E_e, Z)$$

- Cumulative Fission Yields:
  - Nuclear data lib. (JEFF3.3, ENDF/B-VII.1)
  - Fission code (GEFY-5.3)
- Fermi theory + first forbidden transitions treated as Konopinski et Uhlenbeck:
  + Dominant Gamow-Teller (80%)



a) ^{235}U from (1)



b) ^{235}U from (2) (M-H reference)

Double ratio data/simulation with ^{235}U and ^{239}Pu measurement.

- Agreement between ^{235}U(1) and ^{239}Pu measurement
- **Clear inconsistency between ^{235}U(2) and ^{239}Pu: ~5% shift**

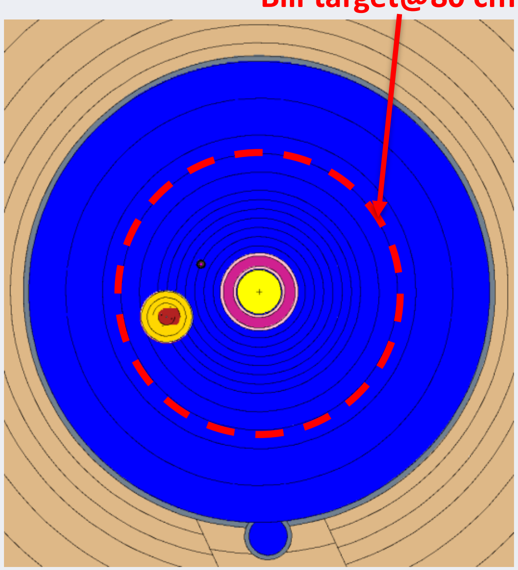
Simulation of the ILL reactor

Review of ILL spectra normalization

- Updated ICC coefficients
- New estimation of the cross-sections
  - ↳ (1) Westcott convention (aproximate approach)
  - ↳ (2) with dedicated reactor simulation

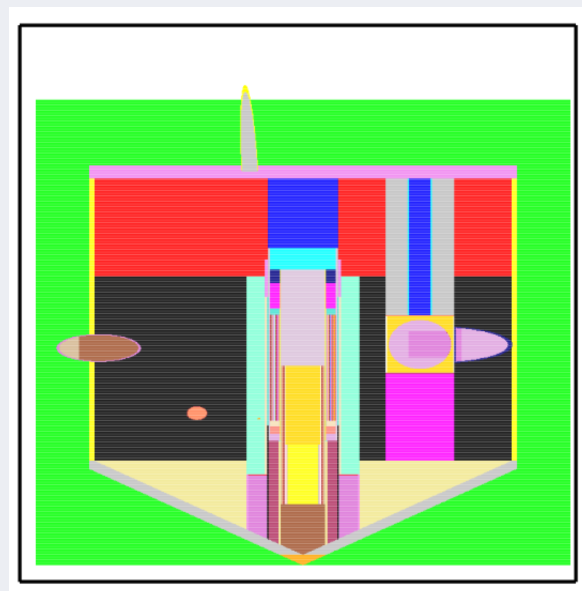
→ Two Monte Carlo simulations of the ILL reactor
- MCNPX-2.5.0
- TRIPOLI-4.10.2

MCNP simulation

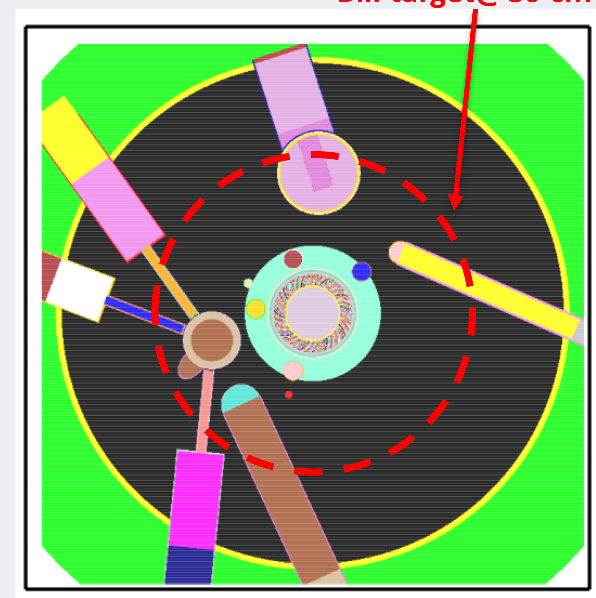


(a) x-y cross-section, $z = 0$ cm

TRIPOLI simulation



(a) x-z cross-section, $y = 0$ cm



(b) x-y cross-section, $z = 0$ cm

Revisited Normalization ingredients (1)

PRELIMINARY

Internal Conversion Coefficients (α)

Spectra normalization

$$N_\beta = \frac{N_f}{N_{st}}\frac{n_{st}}{n_f}\boxed{\frac{\alpha\sigma_{st}}{\sigma_f}}$$

α: internal conversion coefficient (ICC) or beta branching ratio to the relevant state for the beta decay

	ICC value [1, 2] ($\times 10^{-4}$)	ICC value from BrIcc ($\times 10^{-4}$)	new/old values
^{116}Sn (1.29 MeV)	6.47(7)	6.48(9)	1.002(14)
^{198}Au (6 MeV)	1.092(10)(*)	1.071(15)	0.981(16)
^{208}Pb (7.37 MeV)	0.925(9)	1.022(14)	1.105(18)

(*) not provided in but stated to agree within 1% with tabulated data from *[V.F Trusov, Atom. Data and Nucl. Data 10 (1972) 477-510]*

Good agreement with the latest evaluations for ^{197}Au, ^{116}Sn **but 10% higher for ^{208}Pb.**

Revisited Normalization ingredients (2)

PRELIMINARY

Cross-section

	$\hat{\sigma}_{ILL}$	$\hat{\sigma}_{Westcott}$	$\hat{\sigma}_{MCNPX}$
^{197}Au(n,γ)^{198}Au	98.8(3) [1]	103	87.45(12)
^{115}In(n,γ)^{116m}In	140.4(30) [2]	145	123.9(18)
^{207}Pb(n,γ)^{208}Pb	0.709(10) [1] 0.712(10) [2]	0.622	0.546(11)
^{235}U(n,f)	566(3) [2]	565	502(3)
^{239}Pu(n,f)	800(8) [3]	786	696(6)
^{241}Pu(n,f)	1075(9) [4]	1059	936(5)

Wescott convention

$$\hat{\sigma} = \underbrace{\sigma_0}_{thermal}\underbrace{(g + r\sqrt{\frac{T}{293.53}}s_0)}_{non-thermal\ correction}$$

- approximated framework
- r : fraction of epithermal/thermal neutrons above 0.5 eV. $r_{MCNP} = 0.00227$

Mean cross-section used for the ILL spectra normalization assuming a thermal neutron flux ($\hat{\sigma}_{ILL}$), computed assuming a fraction of epithermal neutron ($\hat{\sigma}_{Westcott}$) and computed with MCNP using the JEFF-3.3 database ($\hat{\sigma}_{MCNP}$) .

- **MCNP results**: - averaged results in the D2O at 80 cm of the z-axis with $Z \in [-5,5]$ cm.
  - number in (): deviation for a ± 10cm variation of the target position

➡ **Overall agreement between reference ILL estimation and estimation using the Westcott convention**

➡ **MCNP estimation exhibit lower values for all cross-section (-13-15%) except for ^{207}Pb ($\sim -30\%$)**
↳ **important shift of ^{207}Pb(n,γ) normalization over last evaluation**

Revisited Normalization ingredients (3)

PRELIMINARY

Cross-section ratio

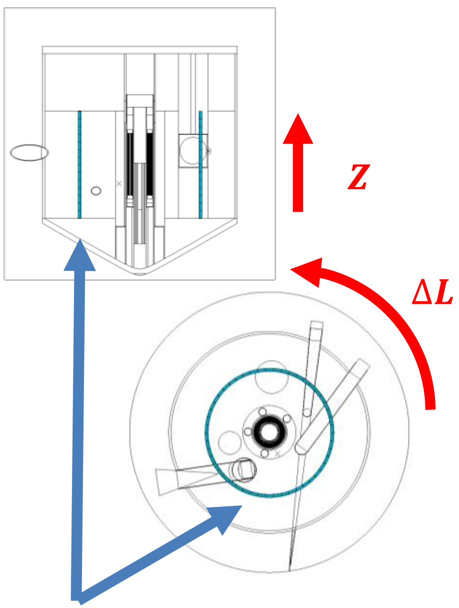
	$\alpha\sigma_{st}/\sigma_f$ (ILL)	$\alpha\sigma_{st}/\sigma_f$ calculated with MCNP	MCNP/ILL data
^{197}Au(n,e^-)/ ^{235}U(n,f)	$(1.91 \pm 0.02)\,10^{-5}$ [1, 3]	$(1.87 \pm 0.02)\,10^{-5}$	0.979 ± 0.010
^{115}In(n,e^-) / ^{235}U(n,f)	$(1.60 \pm 0.03)\,10^{-4}$ [3]	$(1.60 \pm 0.02)\,10^{-4}$	0.998 ± 0.028
^{207}Pb(n,e^-) / ^{235}U(n,f)	$(1.16 \pm 0.02)\,10^{-7}$ [3]	$(1.111 \pm 0.023)\,10^{-7}$	0.955 ± 0.026
		$(1.164 \pm 0.023)\,10^{-7\ a)}$	$0.999 \pm 0.026^{a)}$
^{197}Au(n,e^-) / ^{239}Pu(n,f)	$(1.35 \pm 0.02)\,10^{-5}$[1, 2]	$(1.35 \pm 0.02)\,10^{-5}$	0.998 ± 0.014
^{115}In(n,e^-) / ^{241}Pu(n,f)	$(8.45 \pm 0.19)\,10^{-5}$ [3, 4]	$(8.58 \pm 0.2)\,10^{-5}$	1.014 ± 0.004
^{207}Pb(n,e^-) / ^{241}Pu(n,f)	$(6.1 \pm 0.1)\,10^{-8}$ [3, 4]	$(5.956 \pm 0.17)\,10^{-8}$	0.972 ± 0.033
		$(6.235 \pm 0.17)\,10^{-8\ a)}$	$1.018 \pm 0.033^{a)}$

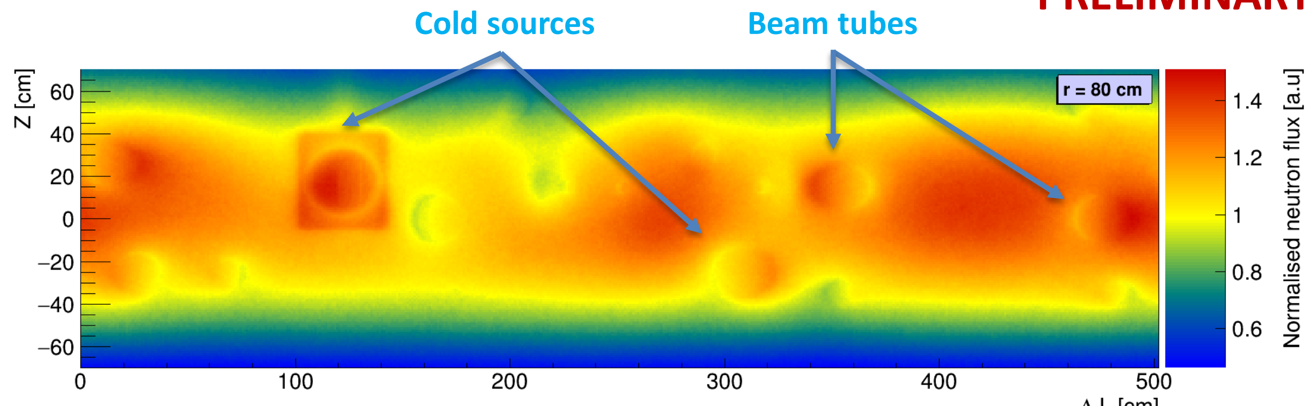
a) Ratios calculated using cross-section from: « Schillebeeckx et al., EPJ A49 (2013) 143, new measurement using γ-spectrometry » (not yet implemented in evaluation). Beside a), all other ratios are using JEFF-3.3 database.

- Simulation with JEFF.3.3: **^{207}Pb(n,γ) previously overestimated by 12%....** **but not using Schillebeecks data**
- The ~4-5% inconsistency appearing in the normalization of the second ^{235}U electron energy spectrum measurement (reference in MH prediction) when compared to the ^{239}Pu spectrum can be reduced by the ~2.5% difference between the two ^{235}U normalisations
- **But preliminary… average results at 80cm in heavy water**

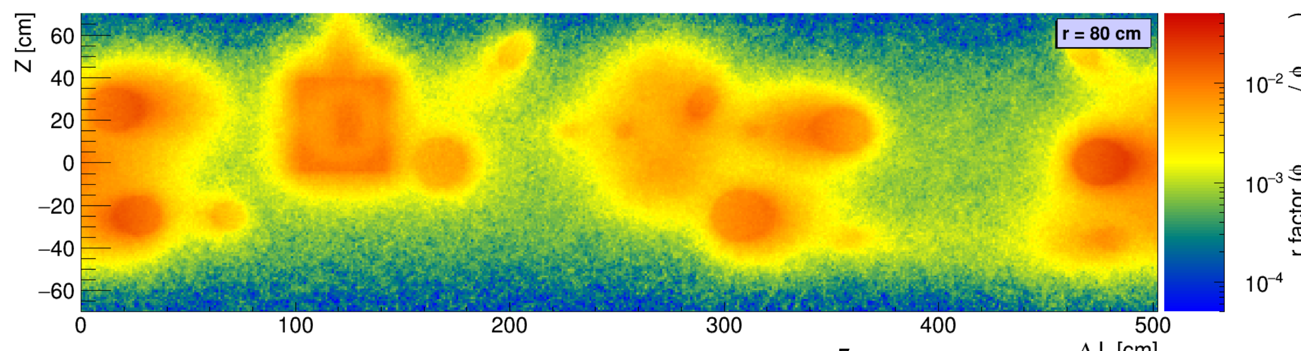
Neutron flux distribution (TRIPOLI)

PRELIMINARY





a) Total neutron flux



b) Epithermal factor r $(E_n > 5.10^{-7}\ MeV)$

Cylindrical mesh:

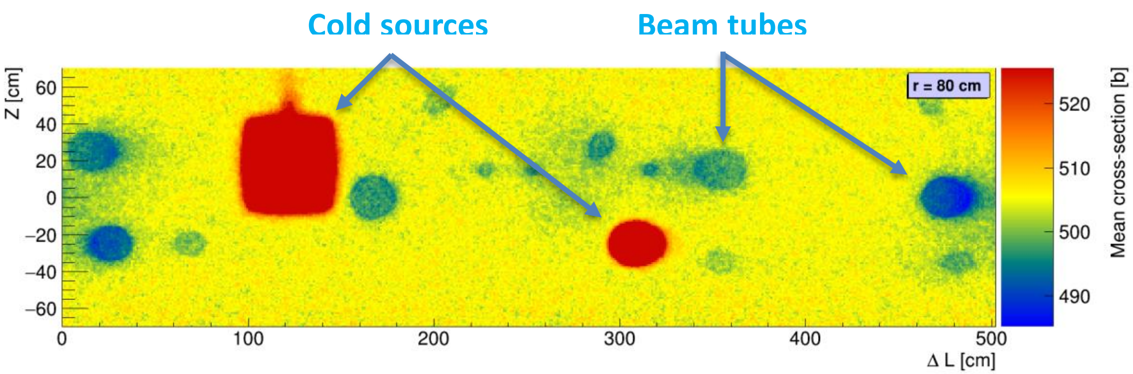
- $R \in [79, 81]$ cm / 1 bins ($\Delta R = 2\ cm$)
- $Z \in [-70, 70]$ cm / 140 bins ($\Delta Z = 1\ cm$)
- $\theta \in [0, 2\pi]$ / 502 bins ($\Delta Larc \sim 1\ cm$)

Neutron flux distribution at 80 cm of the z-axis

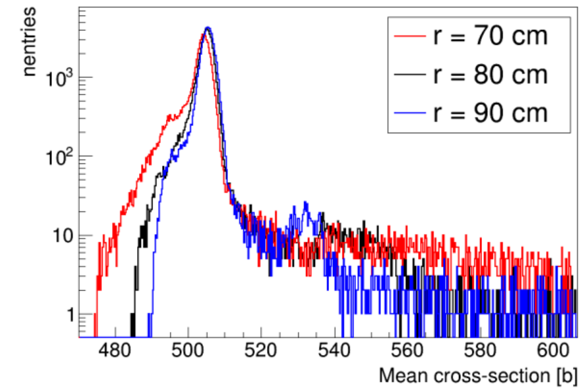
- Local variations: total neutron flux and epithermal contribution perturbed by proximity to sources and neighbor beam tubes
  - ⇘ Hot (graphite) and cold (deuterium) sources used to lower/increase the energy of the neutron that crosses them

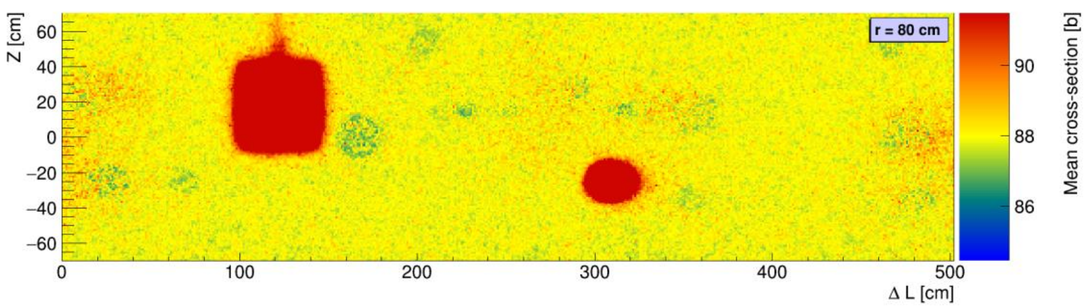
Mean cross-section distribution (TRIPOLI)

PRELIMINARY

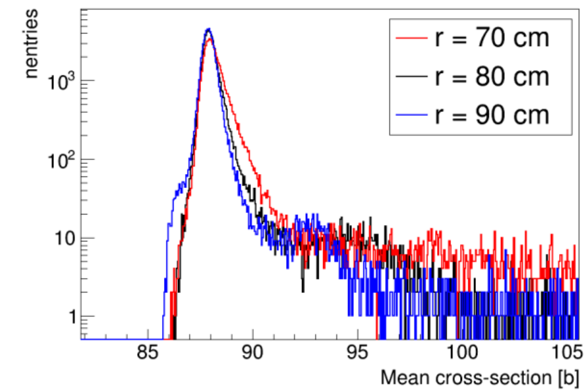


a) $^{235}U(n,fiss)$





b) $^{197}Au(n,\gamma)^{198}Au$



Left: mean cross-section distribution at 80 cm of the Z-axis. Right: mean cross-section distribution over the spatial mesh.

- Flat distribution of local mean cross-section in D2O but non-negligeable effect of the beam tubes (ϕ_{epit} higher).
  - ↳ Potential cancelation in cross-section ratio to be investigated
  - ↳ Potential investigation: implement BILL full experiment (beam tube + target)

Conclusions & perspectives

- **Evidence for ∼5% of incoherency between $^{235}U(2)$ and ^{239}Pu electron-energy spectra.**

- **Preliminary results of ^{235}U, ^{239}Pu and ^{241}Pu spectra normalization investigation using dedicated reactor simulations.**
  - ↳ Importante update of ^{207}Pb partial cross-section (Schillebeeckx et al.: -12%) and ICC (+10%) that mostly cancel.
  - ↳ Averaged results at 80 cm with MCNP ⇒ simulated ratios can partialy explain the 5% normalization incoherency between $^{235}U(2)$ and ^{239}Pu

- Sensitivity studies in progress
  - ↳ Exact position of the experiment unknown: position and surrounding environment influence under investigation. Refined definition of the simulation with implementation of the BILL target tube planned
  - ↳ nuclear database choice and associated uncertainties

- Work in progress: reevaluation of RAA after finalization.
  - ↳ ***Publication coming soon!***

Thank you for your attention!

Backup (1)

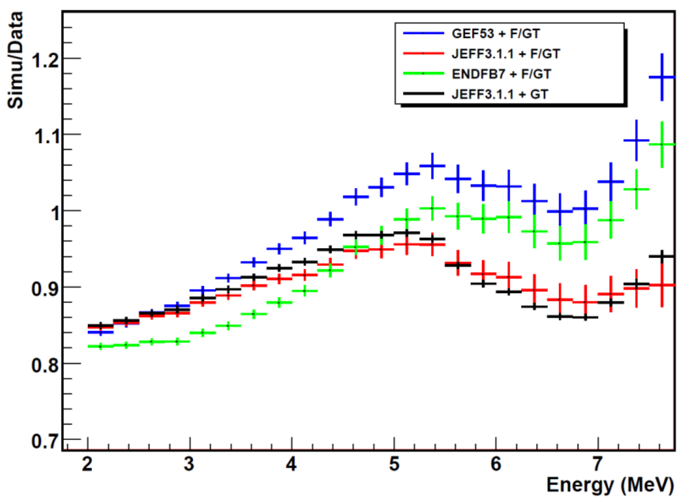
Energy-spectra modelisation

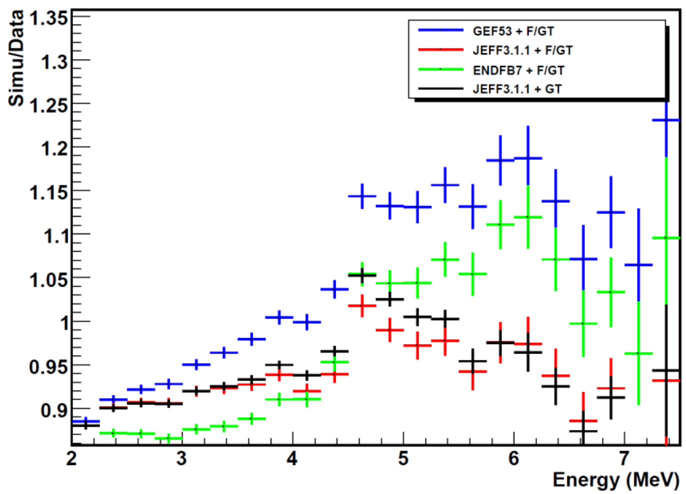
$$S_{tot}(E_e) = \sum_{FP} Y \times \sum_{branch} BR \; S(E_e, Z)$$

- Cumulative Fission Yields:
  - Nuclear data libraries (JEFF3.3, ENDF/B-VII.1)
  - Fission code (GEFY-5.3)

$$S(E_e)dE_e = \frac{g_V^2}{2\pi^3} F(Z,E_e)C_n(Z,E_e)p_eE_e(E_0-E_e)^2L_0(Z,E_e)C(Z,E_e)S(Z,E_e)G(Z,E_e)(1+\delta_{WM}E_e)dE_e$$

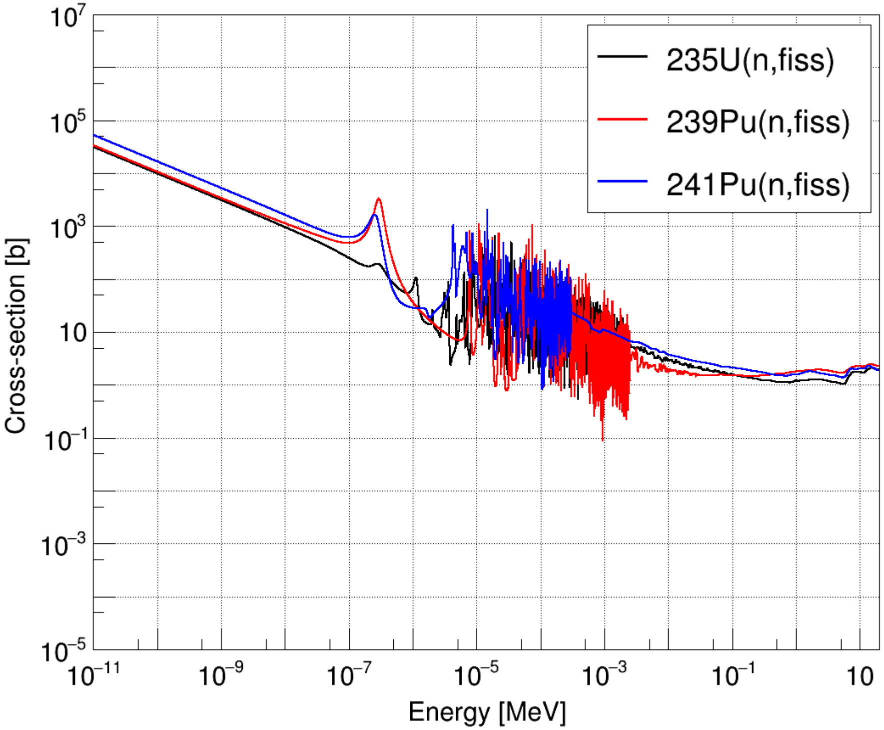
- First forbidden transitions treated as Konopinski et Uhlenbeck
  + Dominant Gamow-Teller (80%)

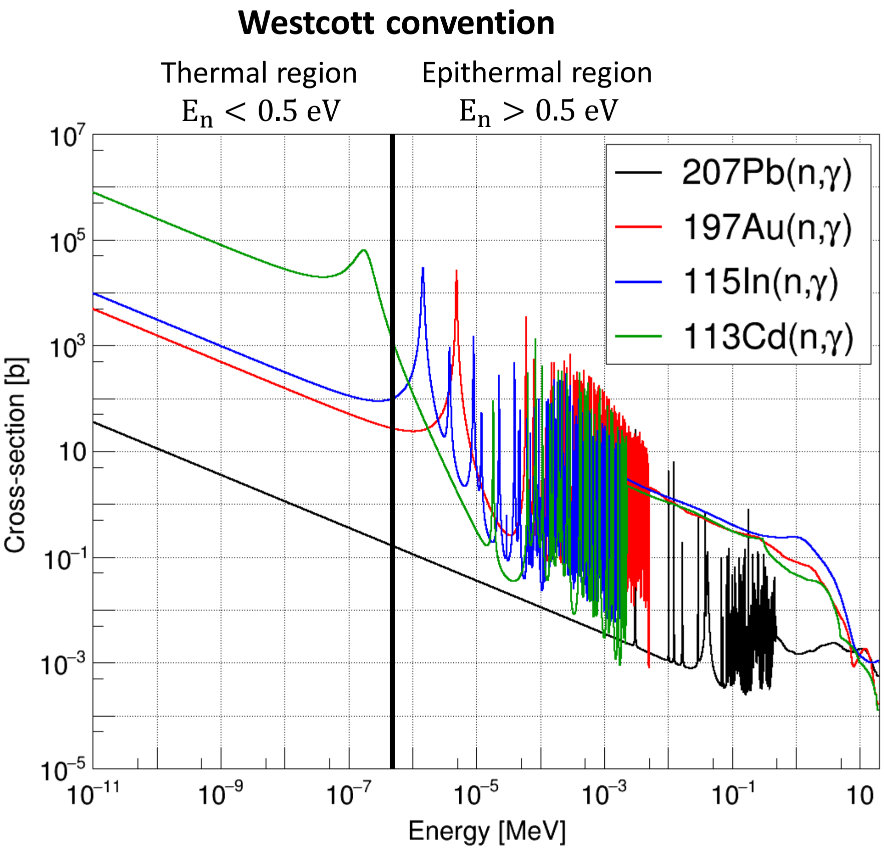




Ratio of the measured to calculated electron-energy spectra for ^{235}U(2) (left)and ^{239}Pu (right)

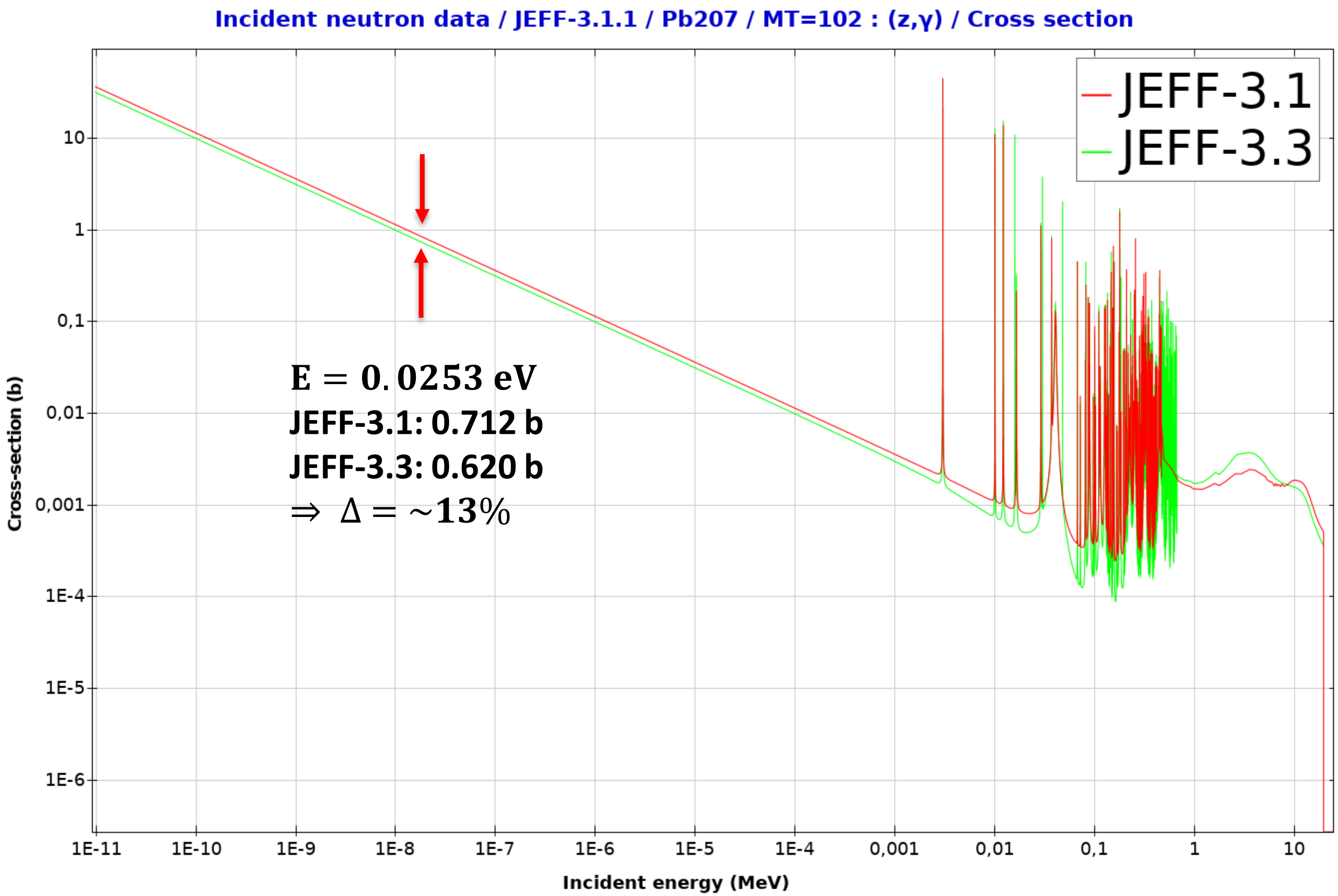
Backup (2)





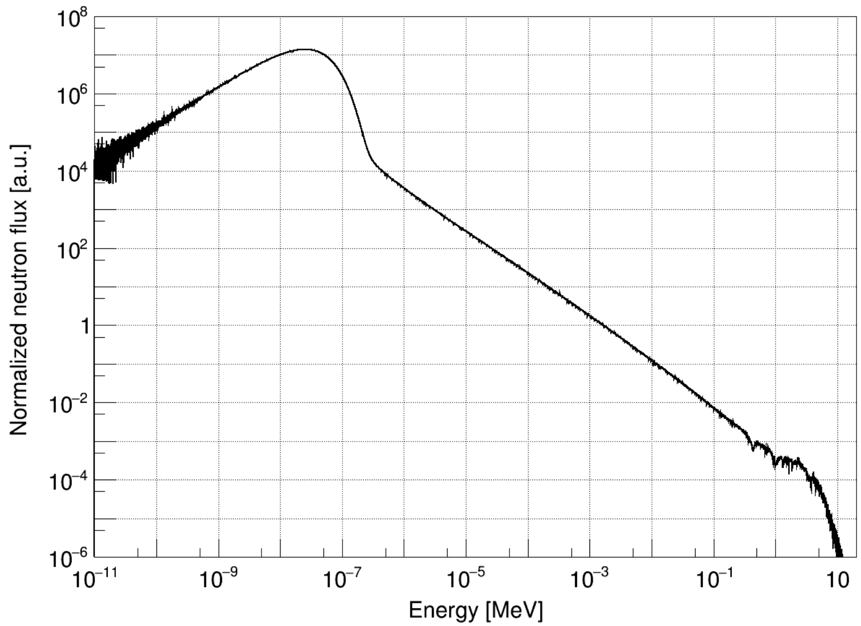
Fission and capture cross-section of relevant isotopes

Backup (3)

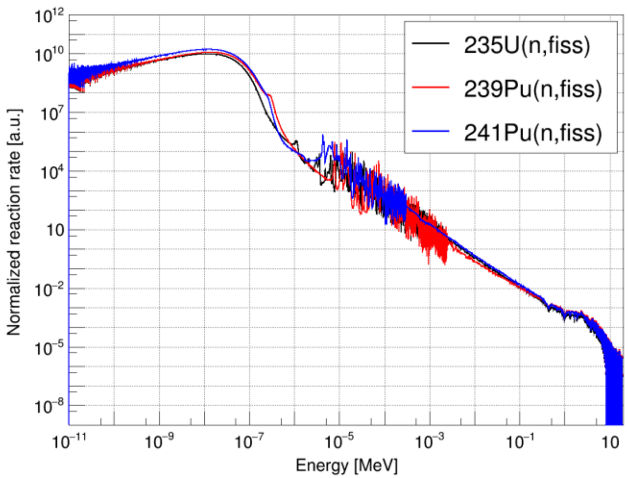


$^{207}Pb(n,\gamma)^{208}Pb$ cross-section for the JEFF-3.1, JEFF-3.3 and ENDF/B-VIII.0 databases

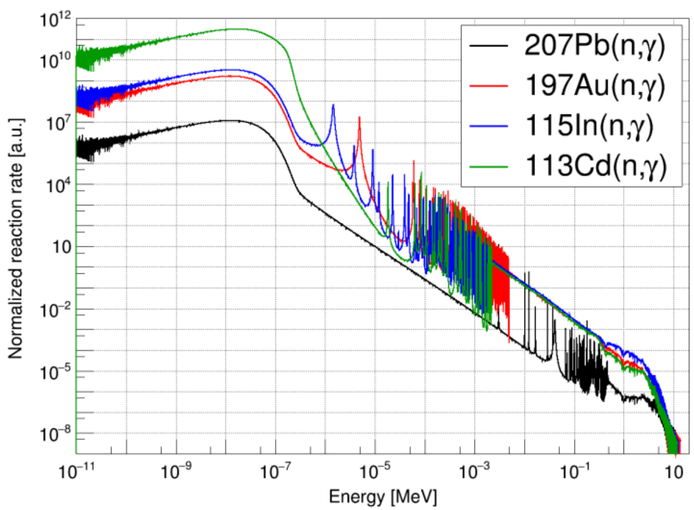
Backup (4)



(a) Neutron flux



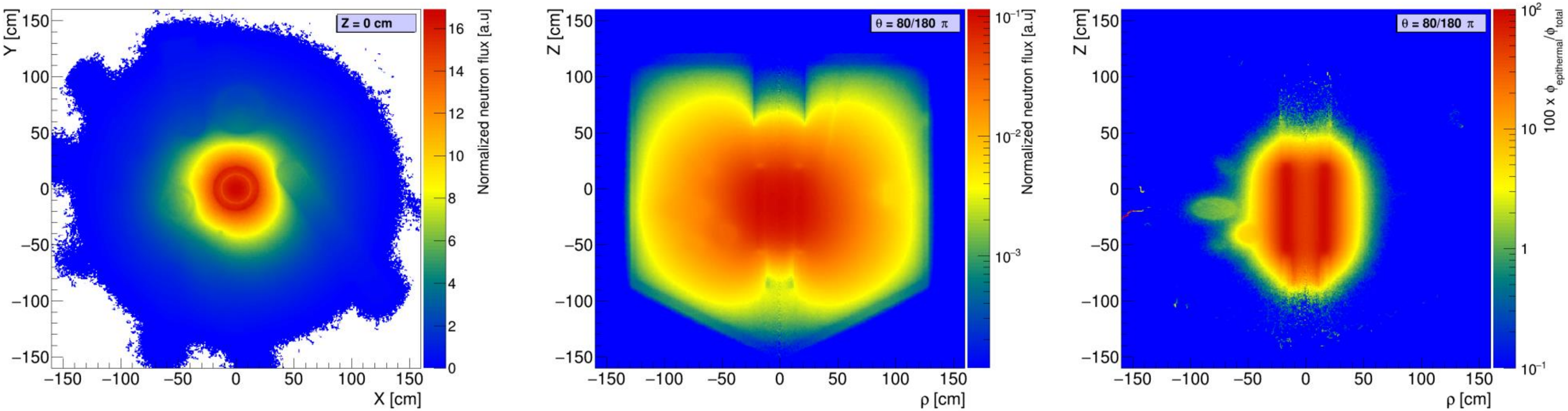
(b) Fission rates



(c) Capture rates

Typical neutron flux spectrum (a) and reaction rates spectra (b,c) for the relevant isotopes in heavy water

Backup (5)



(a) Total neutron flux XY plan, Z = 0 cm

(b) Total neutron flux XZ plan, Y = 0 cm

(c) Epithermal contribution XZ plan, Y = 0 cm

Total neutron flux distribution (a,b) and epithermal contribution (c, Westcott convention $\mathrm{E_n} > 0.5\ \mathrm{eV}$)